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The colours of rock art. Analysis of colour recording and communication systems in rock art research

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ABSTRACT

Colour recording is a crucial aspect of rock art documentation. In this paper, we evaluate different systems to record the colour of rock art and propose a system to describe and communicate it in a reproducible and non-subjective way. Recording and communication of colour in rock art studies, and in general in archaeology, has been treated as dissociated dimensions. Colour rendition charts incorporated into photographic scenes have been used for recording. This process tries to preserve pictures with colours as close as possible to reality. In addition, the use of subjective terms for description and communication of colour has been replaced by the use of standard colour charts (Pantone, Munsell) that are still based on the naked eye observation of the researcher. During recent years, other systems, such as spectroradiometers, colourimeters or mobile platform apps for recording of colour, have been seen as alternatives. Some of these procedures lack internal corroboration or are useful only for recording or only for communication but not for both purposes. That limitation is a contradiction to the basis of colourimetry, the science of colour. The system proposed in this paper contends with the recording and communication of colour in rock art in a comprehensive, reliable and reproducible way, from digital photographic recording to the final communication of colour in publications.

1. Introduction

Description of colour is one of the most crucial tasks in documentation of rock art. The role of colour in pictographs is obvious, as it constitutes a major tangible feature, balanced with morphology or the distribution of figures in a panel. Colour is possibly less important for engravings, although repatination, as a key to age, have obviously similar implications in terms of the repeatability of colour observations. A correct description of colour for pictographs or engravings could provide useful information to correlate motifs in a panel, for a better understanding of scenes and to characterize indexes of conservation in a site.

However, the appropriate description of colour in rock art studies is very often reduced to subjectivity of observers. The procedure to describe colours in rock art has been historically limited to an arbitrary naming based on the criteria of the researcher, who, after naked eye observations, defined terms such as “wine-coloured red”, “deep red”, “blueish brown” and so on. The recording of colour in the post-Palaeolithic rock art of the Iberian Peninsula is a good example of these problems. Researchers such as Breuil or Obermaier, and later, Ripoll and Beltrán, used this unwarranted system. They even characterized pictorial stages based mainly in their description of colour (Breuil, 1920). By the beginning of the 1980s, authors such as Piñón, Viñas or Hernández realized the inconsistency of these procedures and began to suggest that it was necessary to take into account light and humidity conditions to register colour reliably (Piñón, 1982). At the same time, they suggested the use of standardized colour charts as references, such as the Pantone Colour Guides (Baldellou, 1989; Viñas, 1988a,b) and Munsell Soil Color Book (Hernández et al., 1988). These researchers tried to limit subjectivity by turning to these standard charts, but their descriptions of colour were conditioned by the obvious troubles in implementing controlled and reproducible observation settings. Difficulties linked to the use of this type of chart in archaeology were reviewed by Gerharz et al. (1988). In fact, recording and

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reproducibility of colour, even in the controlled environment of a museum, is an extremely complex matter.

The early years of the digital age brought with them the availability of personal computers and graphic editing programs, which were rapidly adopted for the recording of prehistoric imagery. At the beginning of the 1990s, Robert Bednarik developed the IFRAO Standard Scale (Bednarik, 1994; Bednarik and Seshadri, 1995) that tried to become the standard reference for calibration of rock art pictures. Despite its limitations and drawbacks (Echevarría, 2009; Mark and Billo, 1996; Pereira, n.d.) this chart has become a global de facto standard, not only for rock art but also for other archaeological fields (Fig. 1).

The IFRAO scale, in contrast to colour rendition charts such as X-Rite ColorChecker or QPcard 203, lacks any published colourimetric references that could be used for an accurate rendition of colours. A part of its colourimetry is outside of the limits of the usual colour spaces in digital photography (sRGB or AdobeRGB). In addition the whitening agents of the background (Fluorescent Whitening Agents, FWA) and the nature of its tints induce significant deviations in photographic captures and digital developing (Gustafsson, 2010; Pereira, in press-a, in press-b). IFRAO colour chart lacks a specific software for creation of colour profiles and does not have clearly defined workflows that could be useful for an accurate rendition of the colour of a rock art photographic setting. On the contrary, use of a standard colour rendition chart warrants an accurate reproduction of colour as long as a coherent workflow is followed and its quality threshold is verified. However, these procedures produce recordings of colour that cannot be easily communicated; therefore, comparisons among pictographs is not as straightforward as would be desirable. For this reason, the majority of researchers are still currently using the Munsell Color Soil Chart as a reference in their publications. In this context, the arrival of mobile apps for tablets and smartphones, supposedly able to perform real time colour metering in different colour spaces or in Pantone and Munsell charts, have been seen as a solution because they seem able to unify description and communication of colour in rock art and archaeology. Unfortunately this is far from reality.

This impasse requires an alternative approach. In this respect, we consider that it will be useful to refer to the standards of the CIE (Commision Internationale de l'Eclaraige). In the publications of 1986–87, CIE proposed that colour metering, or colourimetry, is the science used to describe with physical magnitudes the spectral band of the radiant power to which the human visual system is sensitive. In other words, the aim of colourimetry is the numerical characterization of colour (Capilla and Pujol, 2002).

The numerical characterization of a colour inside of a coordinate system related to an observer model is possible thanks to standard colour spaces. CIE Lab's colour space (Schanda, 2007) is the main reference colour space because it was designed to describe the human visual model and therefore includes all of the colours that humans can perceive.

The perceived colour of an object is not an intrinsic feature of the object but is determined by observation settings and by the nature of the human observer. Colour is at the same time a psychophysics and psychological phenomenon (Grum and Bartleson, 1980) produced by the processing of the radiant power of visible spectra in our visual system and brain. In this regard, the CIE colourimetry is based on metering of the psychophysics colour stimulus (Schanda, 2007).

However, colourimetry is closely linked to human perception. It is not possible to reliably characterize colourimetric aspects outside of human perception unless a different observer model is used. Spectrophotometry (ISO, 2009) is required for characterization of the properties of reflectance and transmission of light on a given material beyond perception or sensitivity of the human visual system.

The aim of this work is to review the main strategies and procedures of description and communication of colour used in rock art recording up to now. This review will be based on current colourimetric standards and will finally suggest a colourimetric recording protocol that warrants accuracy, reliability and quality control of the final product.

2. Material and methods

Different methods or strategies can currently be distinguished for description of colour, which are based on the involvement of a

Fig. 1. Weathered versions of IFRAO scale are very often used as colour reference for rock art documentation. Other incorrect uses of this scale include self-printing and lamination. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

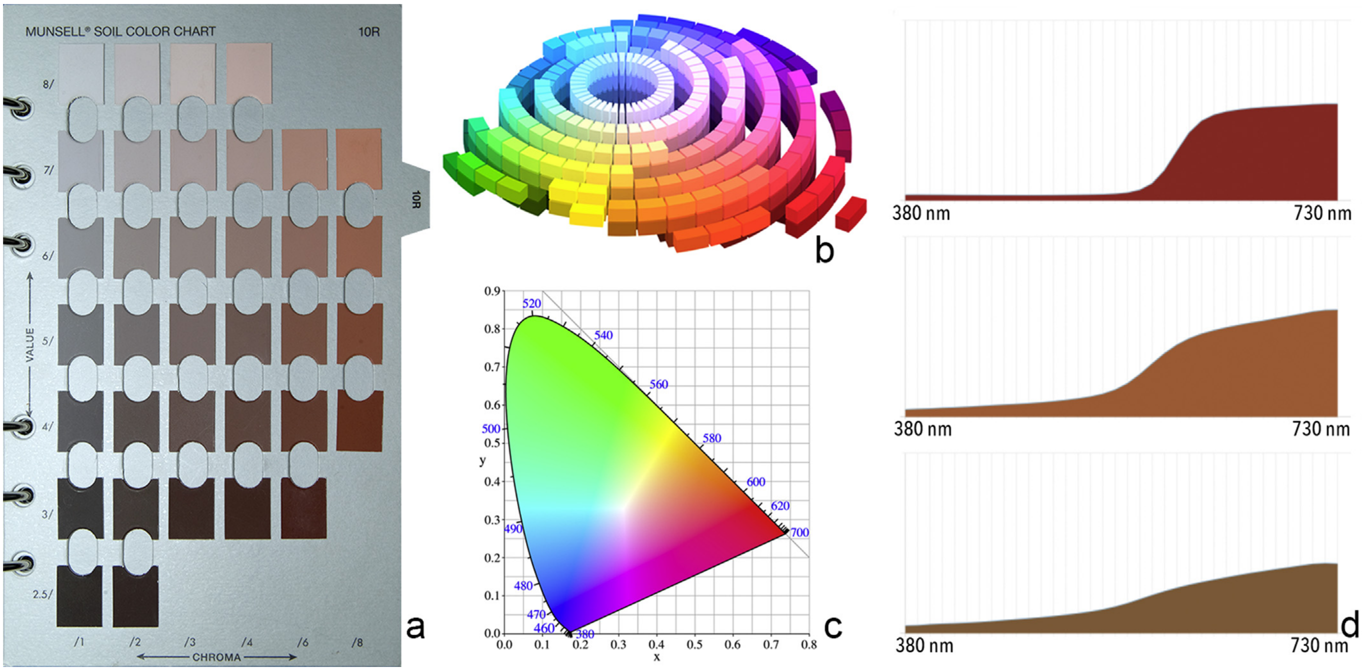

Fig. 2. Data formats of colour. a) Colour codes: Munsell Soil Color Chart; b) three-dimensional representation of the Munsell colour system (http://en.wikipedia.org/wiki/Munsell_color_system); c) colourimetric values: typical horseshoe of CIE Lab 1931 colour space (http://en.wikipedia.org/wiki/International_Commission_on_Illumination); d) spectral values: spectral power distributions (http://spd.jpereira.net). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

human observer, on observation settings and on metering devices. In this regard, colour characterization should take into account three aspects: data format, observation methods and comparison methods.

2.1. Data format

Characterization of colour can be described according to the three following data formats (Fig. 2):

Colour codes (2a): based on colour samples (like Munsell or Pantone charts). They are discrete collections of colour values; therefore, there are colours that are not included in the available samples. Characterization based on colour codes is made by a rounding approach to the nearest colour available in the samples.

Colourimetric values (2b). They can be described through a standard observer model and represented in colour spaces adapted to human perception, such as a CIE Lab.

Spectral values (2c). Description of colour is based on a typical spectral curve known as spectral power distribution.

2.2. Observation methods

2.2.1. Subjective methods

They are characterized by the experience of an observer under specific observation settings. The description of colour in rock art pictographs using the Munsell Color Soil charts can be classified as using this method.

2.2.2. Objective methods

They include metering methods independent of the experience of an observer and the specific observation settings. These methods can be classified into two categories.

2.2.2.1. Direct methods, based on colour metering devices. *Colourimeters*: these devices filter light to measure the intensity of the primary colours, red, green and blue, yielding a colourimetric value. They work in a very similar manner to the human visual system.

Spectrophotometers: these devices (ISO, 2009) can measure the amount of reflected or transmitted light by an object in the different wave-bands of a specific region of the spectrum. The more common spectrophotometers work in the visible region of the spectrum, providing information about a wavelength among 380–730 nm discretized at 10 nm wavelength intervals. Spectrophotometers yield a curve, i.e., radiance values for every spectral band, known as the spectral power distribution (SPD). These radiance values can be used in the form of tristimulus values (XYZ, Lab, LCH, etc.) (Schanda, 2007). Calculation of these values implies the use of standard conditions for observation; the more frequent is the use of the D50 illuminant and the CIE 1931 2° standard colourimetric observer (ISO, 2005).

2.2.2.2. Indirect methods. Currently, it is possible to describe colour by means of a digital image that has been accurately characterized under different standards (Karniyati, 2005; Murphy, 2004).

A digital image can be reliable evidence of a specific feature in a photographic setting, for example, colour, when it is correctly assembled in a workflow that is in accordance with the current standards of colour management (ISO, 2005) or with any other workflow of proven efficacy such as Adobe DNG Camera Profiles. The aim will be to adapt an image to an accuracy criterion instead of other criteria such as utility or naturalness (Yendrikhovskij, 2002); in this context, accuracy refers to the degree of similarity among reality and digital rendition.

The central axis of colour management processes is based on the creation of a colour profile under ICC 1:2001-04 standard (ISO, 2005). The colour profile contains the description of the colour space of a given photographic set recorded by a capture device under specific conditions. These colour profiles are formed by transformation structures such as matrixes, Lookup Tables (LUTs) and tone curves (Hardeberg, 1999) that allow for separation of the observer perception of an image from the colour captured by a specific device (Green and MacDonald, 2002). ICC colour profiles

produce a useful description of the chromatic and achromatic adjustments of an image. These profiles balance out chromatic deviations provoked by CFA filters of the photographic sensors and by the algorithms of raw developing. At the same time, colour profiles allow for examination of tone rendition errors brought about by incorrect exposure values.

2.3. Comparison methods

All colour recording methodologies have to be evaluated to determine their degree of representativeness or accuracy. This is strictly necessary if we are using the indirect methods of colour recording. Colourimetry has provided different colour metering systems for comparisons of samples and references. One of them is known as Delta − e (ΔE^*ab) (Schanda, 2007; Sharma, 2002), and it was designed to determine the distance between two samples of colour. Euclidean distance between two colour samples, also known as CIE76 formula (1) (Sharma, 2002), is one of the more frequently used metering systems.

$$\Delta E^*_{ab} = \sqrt{\left(L^*_2 - L^*_1\right)^2 + \left(a^*_2 - a^*_1\right)^2 + \left(b^*_2 - b^*_1\right)^2} \quad (1)$$

where L is lightness, and a, b are chrominance coordinates.

Lack of perceptual uniformity of this formula gave rise to other metrics, such as CIEDE2000 (2) (Sharma et al., 2005), oriented to produce results perceptively closer to the human visual system.

$$\Delta E^*_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C}\frac{\Delta H'}{k_H S_H}} \quad (2)$$

where L is lightness; C is chroma; H is hue; k_L, k_C and k_H are weighting factors; and S_L, S_C and S_H are compensation factors for LCH (http://en.wikipedia.org/wiki/Color_difference).

These metering systems are used to define quality thresholds in processes related with colour management (Berns, 2001; Melgosa et al., 2001; Stokes et al., 1992).

3. Experimental

Different experiments have been conducted to evaluate which of the observation methods allow colour metering of rock art pictographs according to the criteria of accuracy, reproducibility and quality. Colour measurements were performed in the Marmalo III rock art site (Villar del Humo, Cuenca, Spain) in November 2013. Above average preservation of these pictographs seemed appropriated for these experiments. Approximately 135 Levantine and Schematic style rock paintings are preserved in this shelter. Colour metering was performed on pictographs 036, 037, 053 and 071, individual dots or finger marks that were painted in a single event and very likely with the same paint and colour (Fig. 3), and on figure 134, a Levantine naturalistic bovid approximately 40 cm wide (Fig. 4) (Ruiz, 2006). Measurements were oriented to areas with a different degree of pigment concentration or with diverse patination to test how these factors affected the final results. The selected points exhibit a high level of rock stability; thus, there was no risk of undesired damage by contact. Additional metering was undertaken in areas without paint around the pictographs.

The experiments were conducted in actual fieldwork conditions. Several observation methods were used to record colour of pictographs in a single point, which was identified with a laser pointer; a picture was taken to have a reliable reference of its location. Three different human observers (both authors and F.J. Martínez) measured colour by comparison with a Munsell Color Soil Chart (subjective method) (Munsell, 2000). An X-Rite i1 pro2 spectrophotometer and a Pantone Color Cue 2 colourimeter were used as direct objective methods. Finally, a series of pictures of every point were shot to extract their colourimetric values after applying standard colour management (indirect objective method).

Additionally, some measurements were made with an Apple iPad 4 and an Apple iPhone 4S using mColorMeter and iColorMeter apps (Fig. 5). This type of colour recording should be classed as an indirect objective method because it is not based on direct measurements of light but on an indication of the RGB colour values of a point in a picture taken by those devices, and eventually the results are changed into the Munsell scale.

Calibration of the spectrophotometer was performed on site according to the instructions of the manufacturer. Air temperature in that moment was approximately 8 °C.

3.1. Pantone Color Cue 2 colourimeter and mobile apps

These two methods were dismissed after the first tests because they did not adjust to the proposed quality criteria. Pantone Color Cue 2 is a device developed for colour metering in graphic arts and decoration industries. This colourimeter uses a standard D50 illuminant. The usual working mode is to average three readings of the same point. After that, the device displayed values in the following colour spaces: CMYK, sRGB, Adobe RGB, Lab and XYZ. However, the utility of this device for our purposes is very limited because the values shown in the different colour spaces are not actually the result of raw colour metering but instead a deduction based on the Pantone values. The software of the device seems to carry out a colour metering, deduces the equivalent value in one of the Pantone libraries and, after identification of the closest result to one of the discrete samples of the library, finally translates the Pantone colour name into all of the indicated colour spaces. RGB or Lab values shown should be included in a database stored in the device. When we reached this conclusion, we finished the test with Pantone Color Cue 2 for this experiment. If the device would have shown raw results measured by the colourimeter with D50 illuminant in Lab or RGB, it would have been really interesting to compare those results with the X-Rite i1 pro2 spectrophotometer.

The troubles with mobile platforms and apps are similar in some aspects. These devices are not able to directly estimate the amount of reflected light. As a consequence, mobile apps carry out colour metering in a picture taken by the camera of the iPad or iPhone and thus cannot be considered a direct objective method. In this regard, we should remember that any photographic sensor CCD or CMOS has a CFA (Colour Filter Array) filter installed so colour is rebuilt by demosaicing algorithms. The apps open a picture, perform a reading of the colourimetric values on a point indicated by the user and show a result based on the device dependent RGB value of that point; finally, it is converted into a specific colour space (iColorMeter) or into a Munsell colour system (mColorMeter). Colour metering performed directly on the images implies a high degree of colourimetric inaccuracy because those pictures have not been processed according to a colour management protocol. As a consequence, the results are not reliable. Beside this, pictures shot by one of these devices in similar conditions of illumination and within a time span of a few seconds may exhibit very different colours. The use of flash (available in iPhone 4S) is not a solution; on the contrary, it produces a notable change in the white balance and significant errors of colour rendition because of its low CRI (Colour Rendering Index). The latest versions of the iPhone have been upgraded with a better flash and shooting procedure, so better performance is expected. In any case, these conclusions suggest that these mobile devices and apps could be just as reliable an option if the pictures taken with these cameras were submitted to a

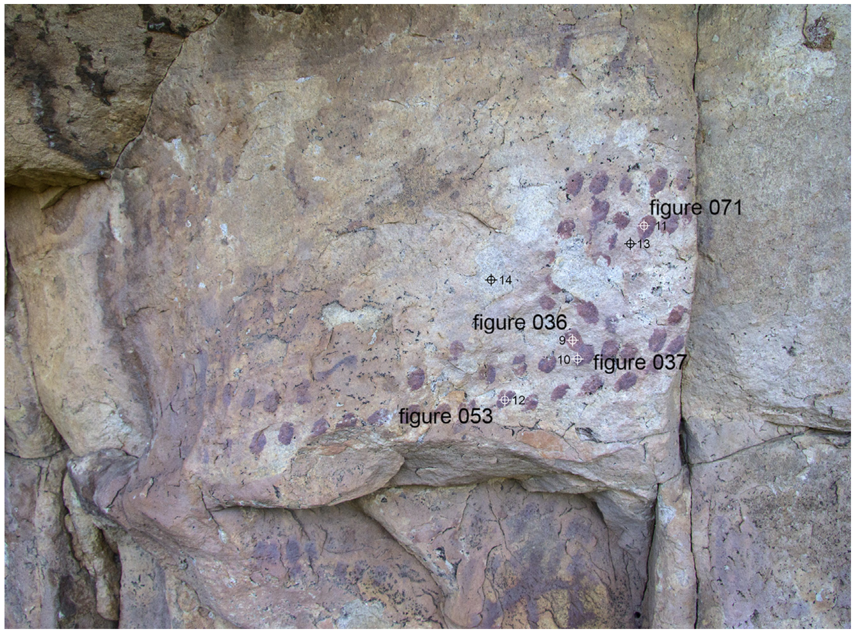

Fig. 3. Group of dots from Marmalo III site (Villar del Humo, Cuenca, Spain), indicating the spots where colour recording was carried out. Unmanaged colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

colour management process similar to the process we are going to describe for pictures taken with a DSLR camera. However, immediacy, the main theoretical benefit of using these mobile apps, disappears in this scenario.

3.2. Munsell Color Soil Chart

Colour identification by comparison with the Munsell Color Soil Chart (2000) was carried out by three different observers in three moments in time. One of us (JFR) performed this type of colour measurement in 2002 while he was working on his PhD dissertation. In March 2013, a third observer (FJMC) and both authors of this work carried out a new reading on a group of pictures of this shelter. Finally, in November 2013, the authors repeated the operation on the same points.

The identification of colours was made in an independent and individual way, and without knowledge of the results of the remainder of the observers. In this manner, we tried to avoid mutual influence in the identification of colours. Obviously, the biggest problem of this method is owing to the fact that colour patches are not representative of the whole continuous colour space that the human visual system perceives, but just a selection of a discrete number of points in that colour space. The influence of ambient light and humidity on the system bedrock-paint is also

Fig. 4. Bull no. 134 from Marmalo III site (Villar del Humo, Cuenca, Spain), indicating the spots where colour recording was carried out. Unmanaged colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

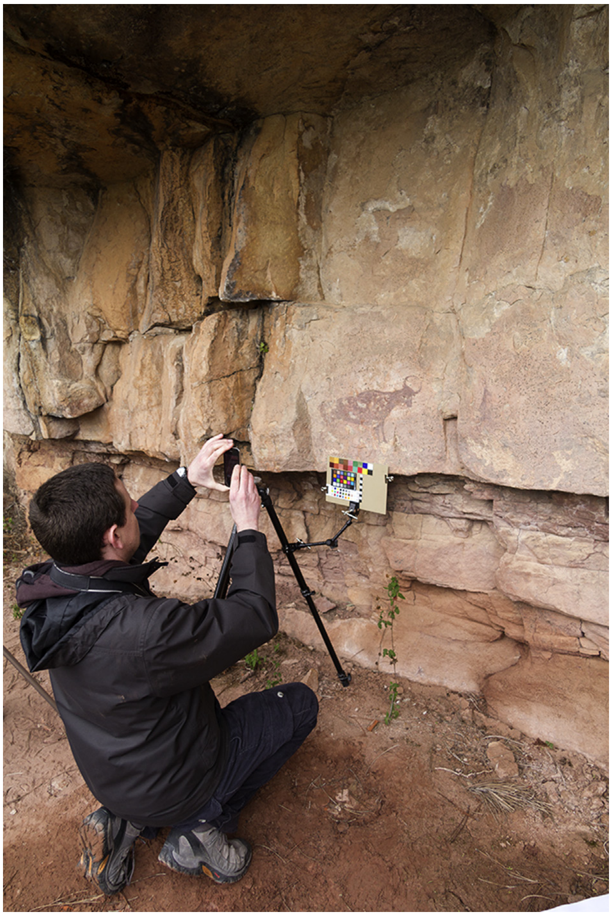

Fig. 5. Francisco Javier Martínez taking a picture of bull 134 using an iPhone 4s and mColorMeter app.

crucial. For this reason, the ambient light conditions (CRI values and colour temperature) were registered by the X-Rite spectrophotometer (Fig. 6a).

The comparison of these naked eye readings with direct colour metering of the spectrophotometer and indirect metering in colour managed pictures was based in spectral and colourimetric measurements carried out with the X-Rite spectrophotometer on every colour patch of Munsell 10R sheet that were saved in a CIE Lab space.

3.3. Spectrophotometer X-Rite i1 pro2 colour metering

Direct characterization of colours by this spectrophotometer was performed in several points of figure 134, one point of the finger spots and in the background (Fig. 6b). Three averaged consecutive readings were made without moving the device. A D50 illuminant was used. The contact area of the spectrophotometer was protected with adhesive tape to avoid any risk of undesired contact with the pictographs. The specific device we have used is a handheld contact spectrophotometer, but we are considering a test of a non-contact spectrophotometer to compare results.

The averaged values were saved as a spectral curve in the visible light range (380–730 nm) and in a CIE Lab colour space (Figs. 7 and 8). Individual readings were recorded by the X-Rite i1profiler software on an Apple MacBook Pro laptop.

A database with several associated matching algorithms (http://spd.jpereira.net) was used for correlating colourimetric or spectral values of the pictographs with the readings of the Munsell colour codes.

3.4. Colourimetric values of colour managed pictures

Colour metering in the selected points was conducted on a picture taken in a photographic scene that included several colour rendition charts. These charts were used for colour management. Colour temperature and CRI were recorded for this purpose. A digital DSLR Nikon D200 was used with an X-Rite ColorChecker Passport card (24 patches), a Kodak Q13 densitometric scale, and different natural pigment samples of a similar composition to the rock art, e.g. carbonates, iron oxides (Fig. 9).

During raw developing, standard colour management was used, and colourimetric accuracy of the results was evaluated (Pereira, 2013). Start-up of colour profiling was done with raw developing of the picture using DCRAW software (Coffin, 2014) to avoid, as much as possible, uncontrolled colour adjustments. The area with the ColorChecker colour rendition chart was identified and extracted from the resulting image. A profiling workflow based on standard ICC.1:2001-04 (Consortium, 2001) was applied on this crop. ArgyllCMS (Gill, 2013) was used for this purpose; in the first stage, colourimetric values of the crop of the colour rendition chart were analysed, and in the second stage, the obtained values were compared with those expected according to colourimetry of the chart using regression algorithms (Hardeberg, 1999). Colour Look-up Tables included in the ICC colour profile were deduced after this operation (Pereira, 2013, in press-a, in press-b).

3.5. Quality control

Evaluation of colour and tonal rendition accuracy achieved during profiling is performed with colour samples similar to the colour of the pictographs and whose colourimetry has been previously analysed. Colour samples of a chemical and spectral nature similar to the rock art (Murphy, 2005) were used to avoid metamerism problems that could induce errors provoked by modifications of the observer model or in the observation settings. In colourimetry, metamerism refers to a similar appearance of two colours when they are illuminated with different light sources. It is caused by the limited response of human eyes in comparison with spectral power distributions. For this reason, the aim was testing of colour rendering in a surface spectrally and colourimetrically as close as possible to our rock paintings. We attempted to avoid deviations caused by the different behaviour of light on materials of different chemical natures.

The threshold of acceptance and comparison was established as $\Delta E^{*}ab \leq 3$. This is based on Stokes et al. (1992), Sharma (2002) and Melgosa et al. (2001) and their proposals for the threshold of tolerance. It was based as well in ISO 12467 and ISO 13655 standards related to quality control in the graphic arts industry.

4. Results and discussion

Values directly recorded on-site by the X-Rite i1 pro2 spectrophotometer were used as a reference to evaluate which of the colour metering methods of rock art pictographs is more accurate. The practical utility to record and communicate colour was taken into consideration as well. These direct objective values were not biased by any intervention on our side; thus, they can be considered as the most easily reproducible and the most reliable. Spectrophotometer readings are recorded in Lab colour space, so the rest of the colour metering values were transformed into this colour space for comparison. Every single colour patch of the 10R sheet of Munsell Soil Color Chart were measured to obtain their colourimetric (Lab) and spectral values. Subjective readings of Munsell chart can be compared in this manner with colourimetric values of the rest of the methods.

Fig. 6. a) José Pereira recording colour temperature; b) Juan F. Ruiz using spectrophotometer to record colour of pictograph 37. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Comparisons have been carried out by means of the ΔE^*ab metering system (Schanda, 2007; Sharma, 2002) that allows for determining the distance between two colour samples and, therefore, the distance of a sample from a reference.

4.1. Subjective observations. Munsell Soil Color Chart

A high degree of error is deduced after the comparison of the readings performed by the three observers on Munsell charts. Subjectivity has a huge impact on the methods based on naked eye observation of a reference colour chart.

Two examples will be used to focus this aspect (Table 1). In the six observations performed on figure 134 in the three tests, there is just one coincidence: value 10R 5/2 was chosen by two observers in November 2013, but the rest of the values were different. If we compare the readings of the three observers in that season, the results are colourimetrically unacceptable; the ΔE^*ab values between the first of these readings and the rest are 20.15 and 11.13. Something similar happens with figure 37. In this case, the observers selected three different Munsell values: 10R 5/4, 10R 6/4 and 10R 5/2. Again, the evaluation of the observers of November 2013 coincided, as did those of observers 1 and 3 in the March 2013 test. The ΔE^*ab values among the readings of the first observer in March 2013 and the rest are 0 and 11.47.

Data are very limited to support a clear conclusion, but the small number of coincidences could suggest that specific conditions of observation have a decisive influence in the selection of a Munsell colour code. We should consider that physiology of perception of colour of the human visual system is not identical for every individual. However, it seems that different observers subjected to similar conditions of observation tend to produce closer results that when an individual carries out several readings of the same object in different moments over a period of time. This could be the reason behind the absence of coincidences among the readings carried by a single observer over the different stages of this experiment. Observer 1 performed three measurements in every one of the indicated pictographs and always proposed a different result. The same happened with observer 2 (JP) in his two readings.

The failure of these observers to repeat their own readings, even under similar conditions of temperature and moisture,

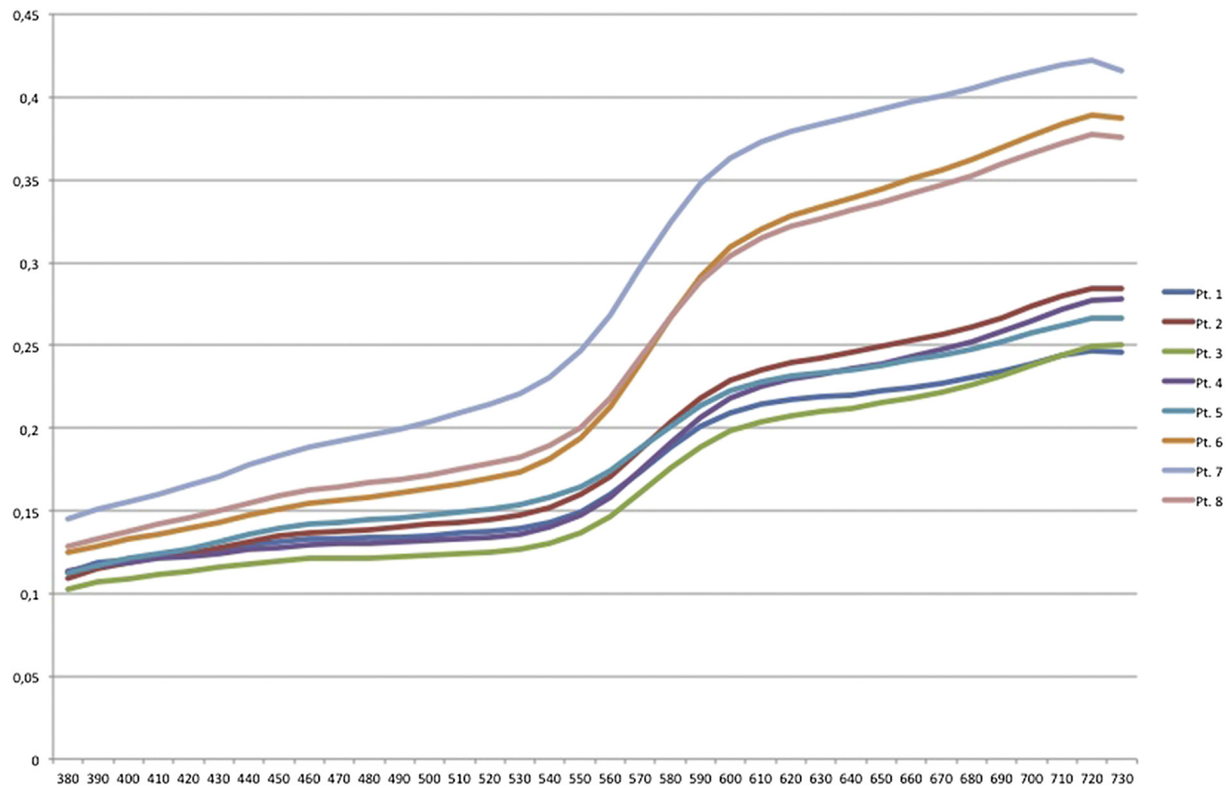

Fig. 7. Colourimetric spectra of the different points measured by spectrophotometer on the bull 134. The background and one sample point with a low density of pigment appear on the upper part of the graph. The overall shape of the pigment samples is indicating that all of them have the same colour. The *Y* axis gradient is caused by different levels of luminosity that can be associated to patination level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

demonstrates the high level of inaccuracy of this method of description of colour. This fact could be linked to the modification of the observation settings or to the perceptual changes of the subjects.

The first option seems more rational; using as a reference the colour that every observer identified for figures 37 and 134 in a single test, it will be realized that the observed colour for both figures repeats in every specific moment to a 50% of cases, that

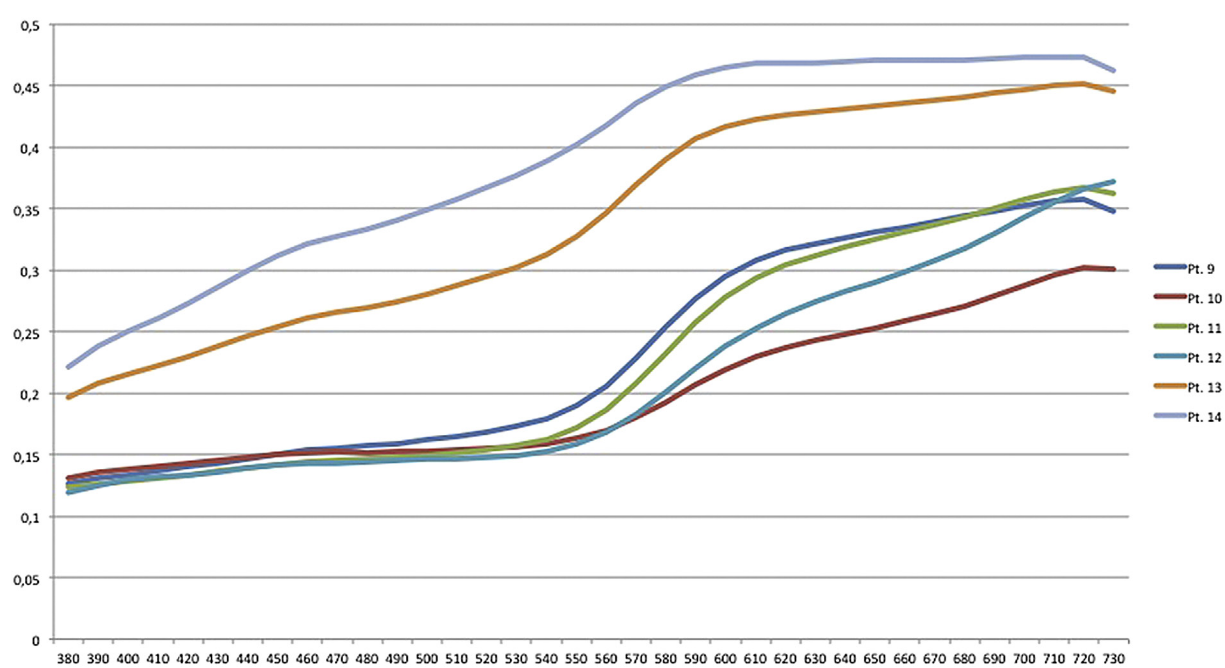

Fig. 8. Colourimetric spectra of the different points measured by spectrophotometer on the finger dots. The background sample points appear clearly differentiated on the upper part of the graph. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 9. Photographic set up for colour management of the groups of dots of Marmalo III. Colour managed picture. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

could raise to 66.6% if observer 3 is dismissed because he just took part in one test. This suggests that observation settings were producing a similar perception when compared with Munsell patches and that observers' perceptions were invariant over the tests.

The last factor to consider is that standard colour charts reduce a continuous colour space to a series of discrete patches. Human observers are forced to select among the options offered in these charts. If this same limitation is applied to the objective measurements of a spectrophotometer, with the goal of approaching a Lab reading to the colour Munsell patch, the result is a $\Delta E^{*}ab \gtrsim 4$ in a 57.1% of cases; an acceptable result but not perfect (see Table 3 in Supplementary material for ΔE of adjacent Munsell patches). In fact, if the results of the naked eye observations in November 2013 test are compared with Munsell patches deduced after the aforementioned approaching a 50% coincidence is observed (M 10R 5/2). The rest of the naked eye readings proposed an M 10R 6/4 value, whereas the spectrophotomer offered a value of *M* 10R 5/3. These results suggest that human observers have a subjective need to emphasize the distance among light and deep tones that are perceived.

Therefore, colour description based just on a subjective method is highly unsatisfactory as a recording and communication system of colour in rock art. This system would be hardly reproducible because of its high degree of dependence of the observation conditions, even if at least light intensity, CRI, colour temperature, air temperature or atmospheric humidity were recorded.

Table 1
Subjective observation on Munsell Color Soil Chart, 10R.

	Value	Chroma
Figure 134 (bull) – 10R sheet		
Observer 1 – 2002	5	4
Observer 1 – 3/2013	4	2
Observer 1 – 11/2013	5	2
Observer 2 – 3/2013	6	2
Observer 2 – 11/2013	5	2
Observer 3 – 3/2013	5	3
Figure 37 (dot) – 10R sheet		
Observer 1 – 2002	5	4
Observer 1 – 3/2013	6	4
Observer 1 – 11/2013	5	2
Observer 2 – 3/2013	5	4
Observer 2 – 11/2013	5	2
Observer 3 – 3/2013	6	4

4.2. Objective methods

The alternative system is using objective methods that warrant a higher level of reproducibility and that produce $\Delta E^{*}ab$ results below the thresholds of tolerance indicated. The values of the recordings performed by the handheld spectrophotometer compared to the values recorded with on-site measurements carried out with iPad4 and mobile apps yielded a $\Delta E^{*}ab > 9$ in 91.6% of cases (Table 2). This result demonstrates that this indirect method is not reliable if pictures have not been previously subjected to a standard colour management.

On the other hand, colour rendition results produced from digital pictures after an appropriated colour management are excellent. Our Nikon D200 photographs yielded $\Delta E^{*}ab < 3$ values in 92.8% of recordings (Fig. 10). The only case with a value of 3.49 is still inside of the threshold of tolerance. These facts demonstrate that colour metering of a rock art pictograph on a properly colour managed picture yield precise, reliable and reproducible results, whose quality thresholds are perceptually comparable to direct observation methods.

4.3. Discussion

The provided results suggest that accuracy in description of colour based on a collection of colour samples (like the Munsell Color Soil Chart) is linked to the number of samples of that collection. In the discrete colour space of the Munsell charts, or any other similar, it is not always possible to reach a colourimetric accuracy $\Delta E^{*}ab \leq 3$ or 4. The reason is that the collections of colour patches oriented to discrimination of colours by a human observer are organized in steps of $\Delta E^{*}ab > 3$ to produce a difference among two samples that can be perceived as different colours by a human observer (Tables 3 and 4 – Supplementary material). Other determinant and intrinsic factors that affect to description of colours based on collection of samples are acumen in discrimination of colours and observation conditions. For this reason, the slight acumen errors or visual judgement produced in discrimination of

Table 2
Colour recording results.

Bull 134	Spectrophotometer					Digital picture			
Sample	L	a	b	Munsel1	Δe 1[a]	L	a	b	Δe 2[b]
1	48.75	9.53	8.8	10R 5/2	3.15	48.89	11.05	8.65	1.46
2	48.86	10.49	10.49	10R 5/2	4.05	48.12	11.48	9.49	1.55
3	47.97	11.79	10.36	10R 5/4	4.21	46.75	12.12	8.5	1.9
4	48.5	11.95	9.83	10R 5/3	3.81	49.13	12.65	9.34	1.2
5	47.92	9.21	9.21	10R 5/2	3.7	47.94	11.00	9.13	1.7
6	54.67	15.52	15.64	10R 5/3	3.9	55.4	14.94	14.31	1.07
7	59.83	12.72	16.41	5YR 6/3	1.2	61.71	12.49	18.34	2.13
8	55.39	13.46	14.55	10R 5/3	3.7	57.7	13.3	15.11	2.19

Bull 134	iPad				Deduced Munsell[d]	
Description	L	a	b	Δe 3[c]	Munsell	Δe 3[c]
1	45.95	3.47	−3.04	11.37	10R 5/2	3.15
2	47.15	5.27	−4.80	12.74	10R 5/2	
3	45.35	2.77	−5.17	14.78		
4	45.35	2.77	−5.17	14.78		
5	51.7	2.75	−8.04	15.54		
6	61.23	9.31	3.52	10.62	10R 6/4	
7	60.33	2.26	2.57	2.13		
8	59.95	7.37	1.00	11.14		

Finger dots	Spectrophotometer					Digital picture			
Description	L	a	b	Munsel1	Δe 1[a]	L	a	b	Δe 2[b]
9	55.46	15.19	14.78	10R 5/3	3.5	55.47	15.63	15.4	0.41
10	51.18	9.67	7.37	10R 5/2	1.9	50.13	10.8	8.39	1.52
11	53.71	15.82	14.29	10R 5/3	2.7	60.13	15.25	14.05	1.66
12	52.98	11.83	9.2	10R 5/3	2.5	51.87	14.11	10.25	2.08
13	66.48	8.63	14.41	5YR 7/3	4.6	66.24	11.00	16.27	2.09
14	70.5	4.71	13.13	10YR 7/2	1.4	67.93	7.34	13.82	3.49

Finger dots	iPad				Deduced Munsell[d]		
Description	L	a	b	Δe 3[c]	Munsell		Δe 3[c]
9	60.31	13.30	3.40	9.14	10R 6/4	5YR 7/2	5.68
10	48.78	4.19	−11.28	15.6	10R 5/2		1.9
11	46.96	12.55	−3.71	14.48	10R 6/4	10YR 8/2	7.33
12	66.18	−0.23	−0.65	18.56			
13							
14							

Observation conditions for bull 134; Lux: 462; Colour temperature: 9992K; CRI: 97.8.
Observation conditions for finger dots; Lux: 645.7; Colour temperature: 11849K; CRI 98.
[a] Δ Value among Lab values of the spectrophotometer and suggested Munsell code.
[b] Δ Value among Lab values of the spectrophotometer and Lab values recorded on managed pictures.
[c] Δ Value among Lab values of the spectrophotometer and Lab values recorded on unmanaged iPad images.
[d] Munsell values deduced according to the procedure explained in the text.

Fig. 10. Colour metering of bull 134 of Marmalo III. Colour managed picture. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

colours yield significant deviations in ΔE^*ab. This problem is emphasized in open-air rock art sites where observation settings are hardly reproducible; in closed environments, such as Palaeolithic caves, this problem could be less important as long as a similar light source is used in successive recordings.

Description of rock art colours based on colour managed digital images using ICC standards or similar procedures (Adobe DNG Camera Profiles) is proposed as a reliable and suitable method to communicate colour inside of thresholds of tolerance for human visual system. This indirect method has been demonstrated to yield results almost as accurate as direct measurements performed by a handheld spectrophotometer. This suggests that on site colour recording of pictographs could be unnecessary. However, it would be strictly necessary to shoot pictures with a reliable colour rendition chart, and it would be interesting to record CRI and colour temperature with a spectrophotometer or photographic thermo colourimeter for every specific scene. A detailed description of practical field method and of colour management for raw pictures are to be published elsewhere.

CIE Lab colour space results are the best option to register colour of rock art because it is the colour space more similar to human perception. Nevertheless, CIE Lab values are difficult to understand and to associate psychologically to real world colours. Therefore, we are aware that while this proposal reaches the desirable scientific consensus it would be necessary an agreement among accuracy and communication of colour. In this regard, the Munsell colour system could still be an acceptable reference as long as an appropriate tool is used to compare CIE Lab values and Munsell codes. A database such as http://spd.jpereira.net or similar could be used for this purpose. Publication of results in ideal conditions should include CIE Lab values, deduced Munsell Color Soil Chart values and ΔE^*ab among them.

Colour management is a solution for colourimetric and tonal deviations induced by photographic sensors based on Color Filter Arrays (like Bayer matrixes) and routines of chromatic interpolation and demosaicing. Nevertheless, the own nature of transformation routines based on Color Look-Up Tables (Lee, 2005) induce errors that should be taken into account for future works even when they are inside of perceptively acceptable levels.

5. Conclusions

The use of colourimetrics values described in a specific colour space, such as a CIE Lab, and the use of devices that produce an objective description of colour are essential to describe rock art colour in an accurate and reproducible way, even in complex recording environments such as open-air rock art sites. Human differences/acumen in identifying colour will always lead to subjective and potentially non-repeatable identification in the field.

The workflow proposed in this paper is a reliable solution for recording of the colours of rock art. Digital photography submitted to coherent workflows of colour management is an accessible and especially objective procedure. A picture including a professional colour rendition chart with a well-known colorimetry, recorded in raw format, developed following a standard colour management workflow, to finally get an ICC profile will produce results as accurate as those of a spectrophotometer. This system has very low colour rendition errors and is, in any case, below the threshold of perceptive tolerance of the human visual system. In this manner, the digital image can be transformed into a container of objective colourimetric information with high levels of reliability. The use of this procedure will ensure that this crucial information of rock art pictures and engravings is recorded for the future.

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Appendix A. Supplementary material

Supplementary material related to this article can be found at http://dx.doi.org/10.1016/j.jas.2014.06.023.

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